29th January 2024

Aerial Dye and Drogue Release Report

Quanterness

Summary

Cooke Aquaculture Scotland (CAS) undertook a dye and drogue release survey at the proposed Quanterness site in December 2023. This study mapped the propagation of dye plumes and drogues to calculate a horizontal dispersion coefficient for use in future bath modelling applications.

Four releases of Rhodamine WT were conducted over 1 day at key points of the tide. For each release, dye plumes were mapped using georeferenced images taken from an Unmanned Areial Vehicle (UAV). The horizontal dispersion coefficient was calculated using the mean squared displacement and time lag from the initial release. Results show an average horizontal dispersion coefficient of 0.09 m^2/s.

A second survey was conducted using six drogue releases, mapping longer-term particle fate and dispersion. Drogues were fitted with onboard GPS loggers, allowing area-based tracks to determine displacement and dispersion with lag time. The results recorded an average horizontal dispersion coefficient of 0.117 m^2/s.

It is recommended that the combined average of the two surveys is used in future particle tracking modelling. For the proposed Quanterness site, a horizontal dispersion coefficient of **0.105 m^2/s** should be used.

1. Introduction

The horizontal dispersion coefficient plays an important role in the dilution of the aqueous solutions discharged into the marine environment. To ensure high environmental standards are maintained, the measured dispersion coefficient can be used in numerical models to predict the distribution and concentration of a solution or particle released.

The horizontal dispersion coefficient accounts for the random turbulent particle motion that is not inherently incorporated within the primary hydrodynamic model. This is often impossible to include due to the resolution and associated computational resource required. The application of a horizontal dispersion coefficient provides a more computationally economical method of including these processes within a wider scale model. This enables particles to be tracked over a longer period and can determine particle fate on a much larger geographical scale.

The physical dispersion process is highly variable in time and space. In the coastal marine environment, the main contributors arise from tides, bathymetry, wind, waves and freshwater input. These factors introduce irregular motion within the water body, with turbulent length scale ranging from the micro (<1m) to the macro (>1km). The dye and drogue survey method combines these factors into a single value that best represents the mixing at the site, allowing the highly complex chaotic motion to be translated into representative particle motion.

1.1 Site description

The proposed development at Quanterness expands and repositions the existing site. The proposed site will comprise of 14 x 120m circumference pens, arranged in a 2 x 7 formation within a 70m x 70m mooring grid. The expanded site is relocated 1010m to the NW of the existing site in a deeper, more exposed location (342733E, 1014921N). Benthic modelling of the proposed site using the SEPA default NewDepomod model indicated a maximum biomass of 1925 tonnes was compliant with all EQS criteria. This provides a stocking density of 14.99kg/m^3 during peak biomass. Further information on the existing and proposed site infrastructure and pen layout is presented in Table 1.

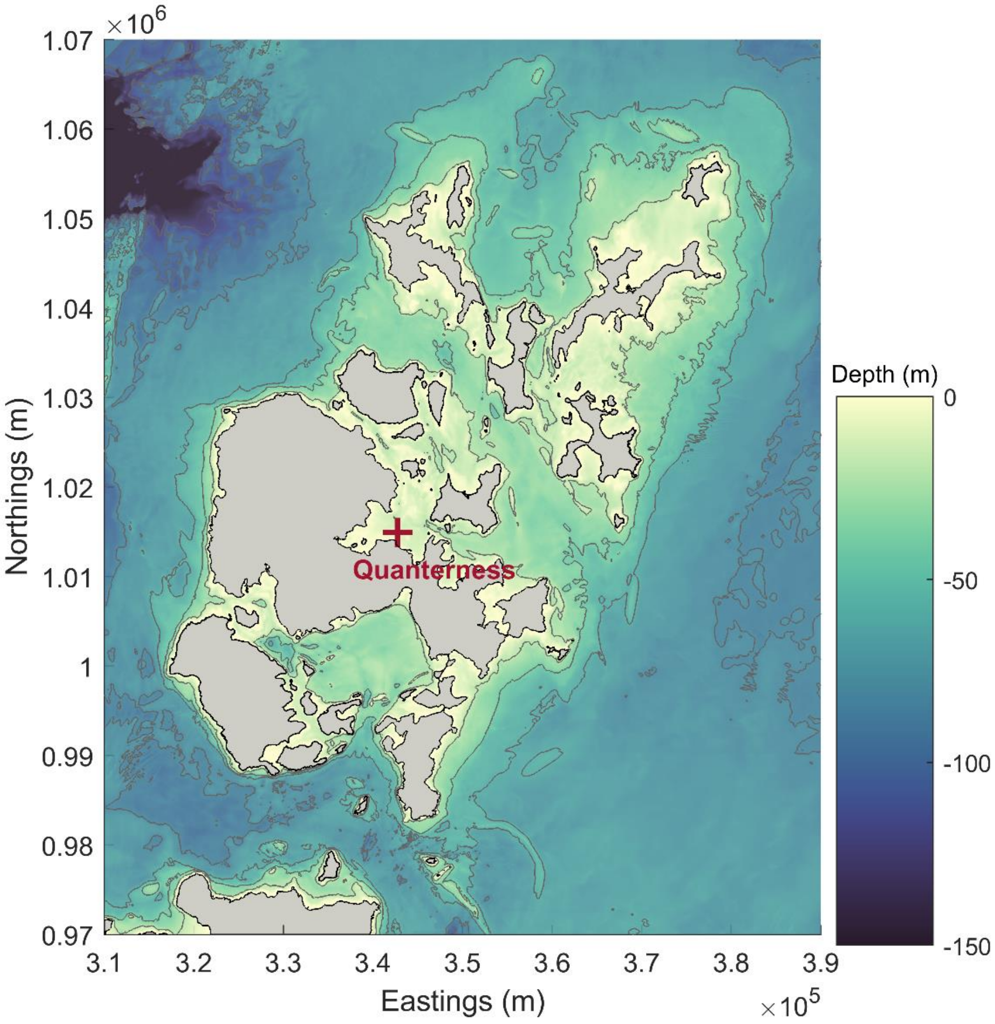

Figure 1. Site location (red cross) and bathymetry with depth contours at 20m intervals.

Table 1 – Site infrastructure and pen layout.

	West Shargun Shoal (Existing)	Quanterness (Proposed)
Consent number	CAR/L/1001931	CAR/L/5003381
Company	Cooke Aquaculture Scotland	Cooke Aquaculture Scotland
Receiving water	Bay of Kirkwall	Wide Firth
Site centre (OSGB36)	343220.24E, 1013947.6N	342733E, 1014921N
Current meter location (OSGB36)		342719E, 1014925N

Distance to shore (km)	0.56	0.9
Average water depth (m)	13.46	15.18
Maximum biomass (t)	600	1925
Total number of pens	8	14
Number of pen groups	1	1
Formation	2 x 4	2 x 7
Pen group orientation (º)	8	0
Pen shape	Circular	Circular
Pen circumference (m)	90	120
Mooring grid (m)	50	70

2. Methodology

Dye Release

To measure and calculate the dispersion coefficient, 4 dye releases were performed on the 30th of November 2023. An Acoustic Doppler Current Profiler (ADCP) was deployed at 342719E, 1014925N for the duration of the survey and recorded tidal phase and surface current velocity. The details of the dye release time and track duration are shown in table 2.

Table 2. Details of the individual dye release.

	Dye Release Time (GMT)	**Plume track duration (mm:ss)**	**Number of aerial images**	**Tidal phase**	**Corresponding drogue release number**
R1	30/11/2023 09:03:20	19:48	41	Peak flood	R1
R2	30/11/2023 11:02:20	20:30	42	High water	R3

R3	30/11/2023 13:33:46	17:30	36	High water ebb	R5
R4	30/11/2023 14:58:41	16:00	33	Slack water ebb	R6

Dye releases were distributed throughout the day and are shown with respect to water level and current speed in figure 2. This covers a range of conditions including peak flood, high water and peak ebb tide/slack water. These stages of the tide were considered to be representative of the location.

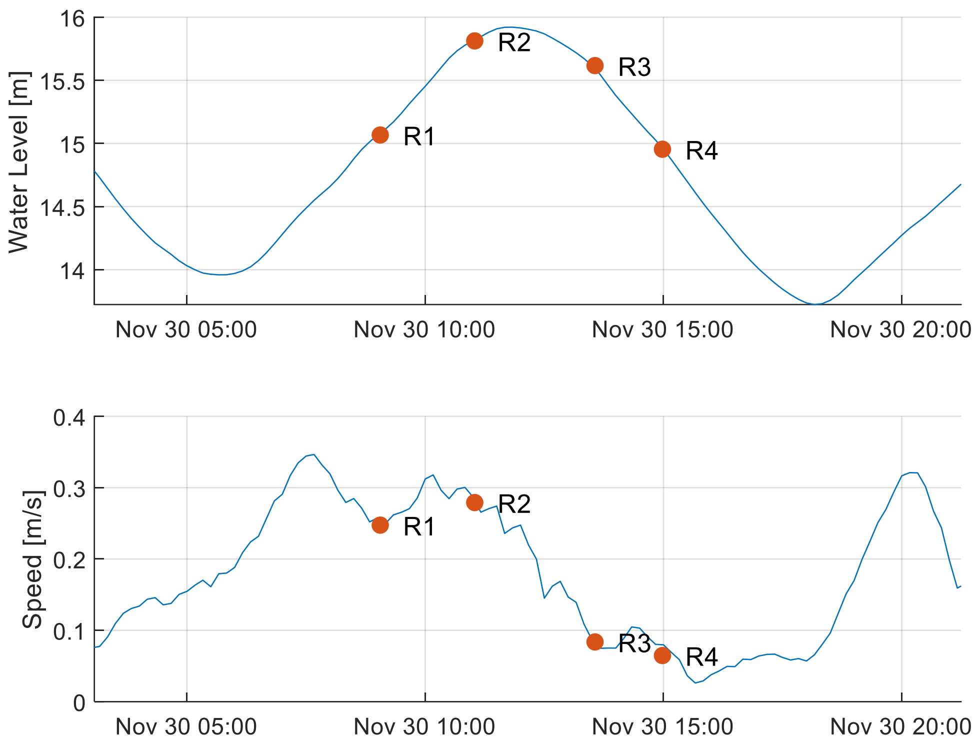

Figure 2. Tidal elevation and near- surface current velocity with the dye release times.

The dye, Rhodamine WT, was released at a single point at the site centre location. The advection and dispersion of the dye patch was monitored by a quadcopter UAV. Images were taken in a downward orientation approximately every 30 seconds for up to 20 minutes. Metadata from each image containing GPS, time and camera gimbal movement (yaw, pitch and roll) were used to geo-reference each pixel within the images.

Post-processing of the images used colour values to automatically identify the dye plume boundary. This allows the outer perimeter of the dye patch to be mapped in geographic space. An example of the image processing and dye plume identification is shown in figure 3. This shows the deployment of the dye and subsequent 5 images. During this early stage of the dye release, the dye plume is shown to be concentrated and the boundary indicated with a black line, accurately mapping the perimeter. The white dots in the SW corner of the image are the drogues, these correspond to drogue release 5 (R5). To prevent staining of the drogue subsurface sails, these were released several minutes before the dye.

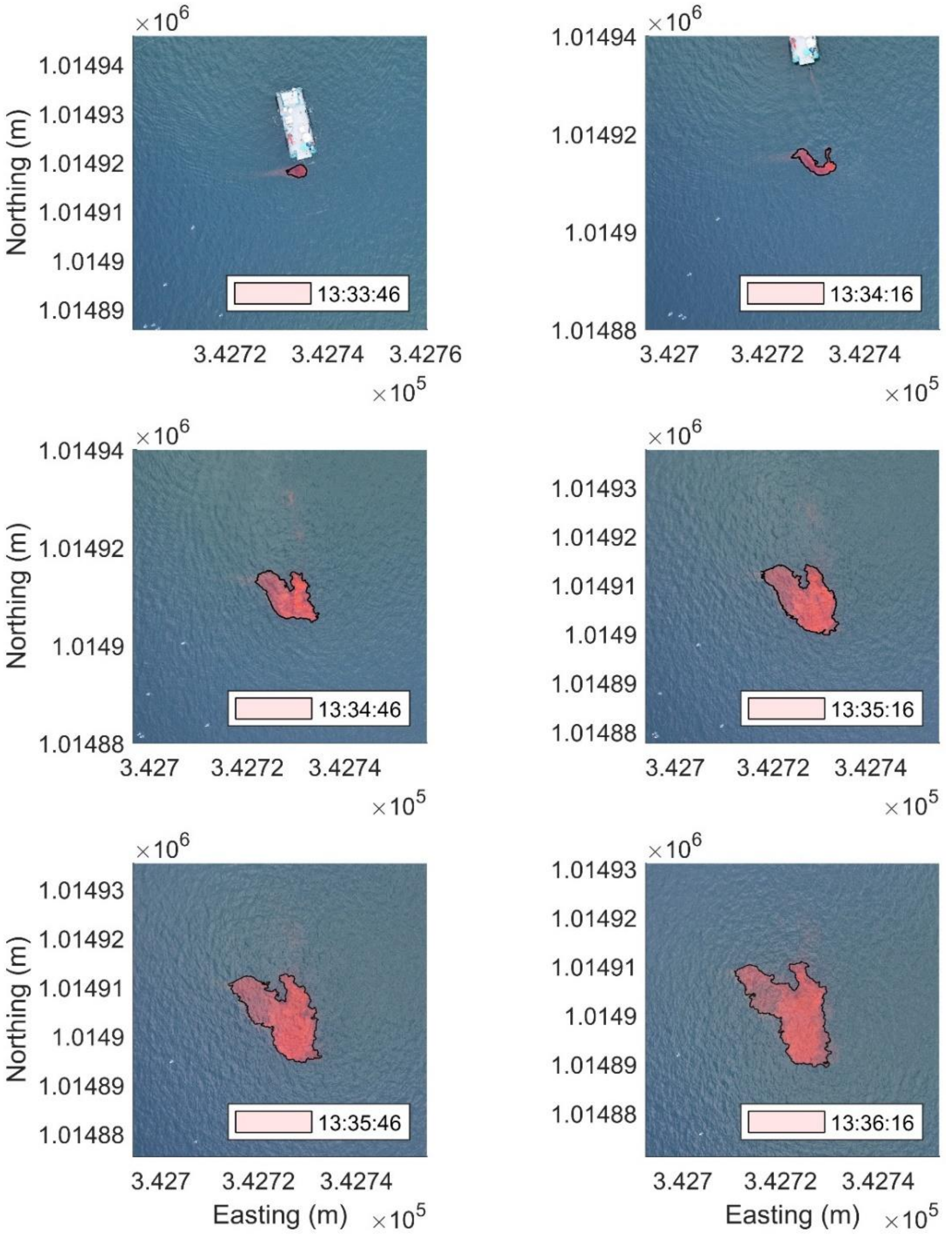

Figure 3. Georeferenced aerial image for the R3 release. The black line shows the extent of the measured dye plume with the image time (GMT) located in the bottom right corner.

Einstein's theory to describe Brownian motion applies the mean squared displacement (MSD) to convert the 2-dimentional plume area to a displacement value from a central location. This central location used the centroid of the time dependent dye boundary.

$$MSD = \frac{1}{N}\sum_{i=0}^{N}\left|x^{i}(t) - x^{i}(0)\right|^{2}$$

$$K_h = \frac{1}{4}\,MSD/dt$$

where, N is the number of points in the boundary, $x^i(t)$ is the *i*-th points distance of the dye plume boundary and $x^i(0)$ is the centroid location of the plume. The dispersion coefficient (Kh) is then calculated using the synchronised time step (dt).

A linear fit is applied to the MSD and time interval data, where the dispersion coefficient (Kh) can also be calculated from the fit gradient.

Drogue Release

Six drogue releases were performed on the 30th of November 2023. This occurred on the same day as the dye release study, allowing the same ADCP data to determine tidal phase and near surface flow speeds. The details of the drogue release time and track duration are shown in table 3 and figure 4.

Table 3. Details of the individual drogue releases.

	Drogue Release Time (GMT)	Plume track duration (mm:ss)	Number of Drogues	Tidal phase	Corresponding dye release number
R1	30/11/2023 09:03:00	25:00	5	Peak Flood	R1
R2	30/11/2023 09:53:00	50:00	5	-	-
R3	30/11/2023 11:08:00	50:00	6	High water	R2
R4	30/11/2023 12:23:00	50:00	5	-	-
R5	30/11/2023 13:33:00	50:00	5	-	R3

R6	30/11/2023 14:58:00	45:00	5	Peak ebb Slack water	R4

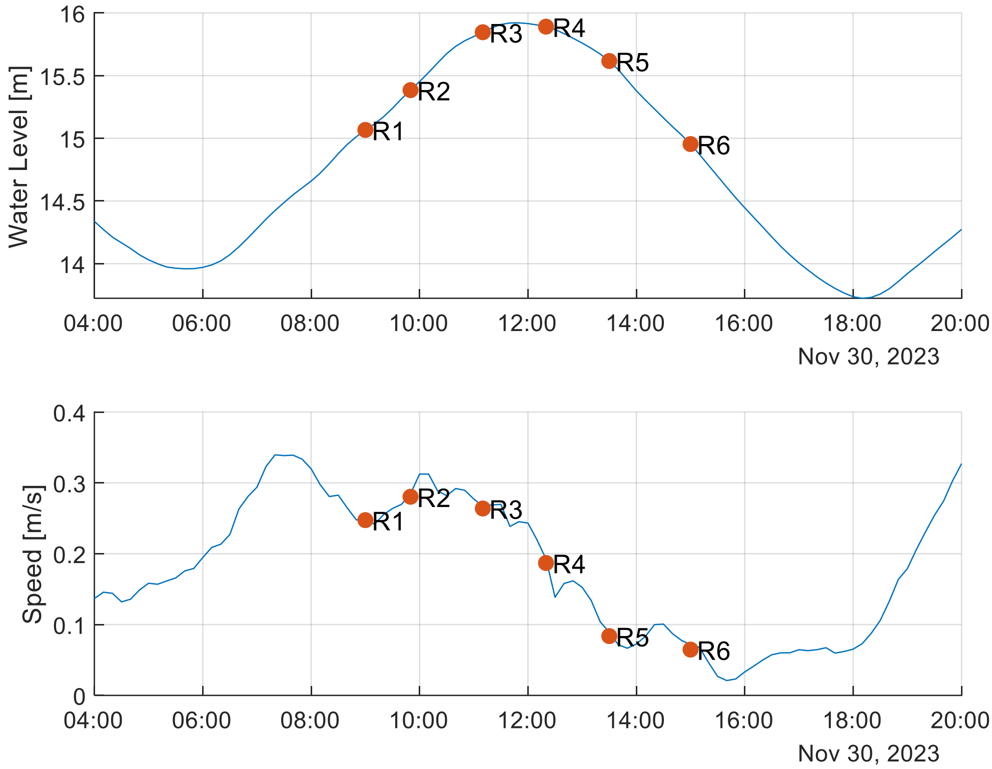

Figure 4. Tidal elevation and near surface current velocity with the drogue release times.

Drogues were released at a single point at the proposed site centre location. Each drogue consisted of a sub-surface sail, similar to a CODE/DAVIS drifter, with a surface buoy housing an Iridium GPS system. Each release lasted approximately 1 hour with a sample interval of 5 minutes. A diagram of the drogue used is shown in figure 5. These drogues are reduced in size to improve performance in shallow coastal waters, these modifications also improved deployment, retrieval, and storage options once on the vessel. Due to the non-standardised sizing of the drogue, the drag area ratio was calculated to determine the drag between the surface and subsurface equipment. This calculation is shown in Table 4, where drag coefficient is estimated based on the profile shape of the equipment. The drogues are shown to have a drag ratio of 61.11. The Global Drifter Programme Barometer Drifter Design Reference (A. Sybrandy et al, 2009) states that the drifter should maintain a drag area ratio of more than 40. This criterion is comfortably achieved by the drogue used in this study.

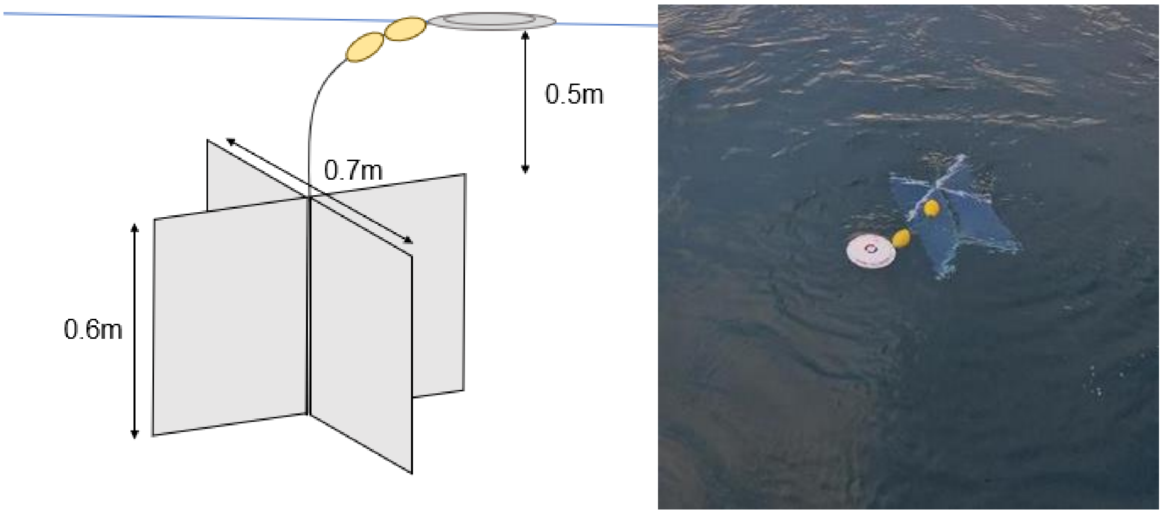

Figure 5. (left) Diagram of drogue with measurements. (right) Photo of drogue sinking immediately after deployment.

The effect of the wind on the drogue can be quantified using the wind slip equation parametrised in Lumpkin and Pazos (2007). This determines wind slip (U_{slip}) as the wind-induced velocity of the drogue. This relationship is shown as

$$|U_{slip}| = \frac{A}{R} U_{wind}$$

where R is the drag area ratio, A is a constant equal to 0.07 and U_{wind} is the wind velocity.

The wind slip for a variety of operational wind speeds is shown in Table 4. This indicates low wind-induced velocities associated with the drogue, even in relatively strong winds. To ensure minimal wind effects on the drogues, wind slip should ideally be kept below 1 cm/s. For the drogues used in this study this equates a maximum wind speed of 8.7m/s (19.5mph).

Table 4 Drag area ratio and wind slip of drogues.

Sub-surface Equipment			
	Area (m^2)	**Drag coefficient (C_d)**	**Drag Area (A x C_d)**
Sails 0.35m x 0.6m	0.42	1.4	0.588
Mast 0.6m x 0.022m	0.015	1	0.015
Tether 0.5m x 0.004	0.002	1.17	0.002
Surface Equipment			

Buoy (x2) 0.075m x 0.12m	0.007	0.47	0.007
Drifter Sensor 0.25m x 0.035m	0.009	0.1	0.001
Drag Area Ratio			**61.11**

Wind Slip				
Wind Speed			**Wind induced slip (m/s)**	**Wind induced slip (cm/s)**
Beaufort Scale	**mph**	**m/s**		
2	7	3.1	0.0036	0.36
3	12	5.4	0.0062	0.63
4	18	8.0	0.0092	0.92
5	24	10.7	0.0123	1.23
6	31	13.9	0.0159	1.59

The post-processing of the drogue data synchronises all deployed drogues to the same time step. The dispersion coefficient is calculated at each time interval using the MSD as stated in the dye release section above.

3. Results

Dye Release

The dye boundary mapping is applied to all images for each dye release (R1 – R4). The dye boundaries are stored as stacked polygons for each release, an example of these stacked layers is shown in Figure 6. This shows 18 out of 36 timesteps plotted with the background image as the first true colour image in the sequence. This illustrates the expansion of the plume over time with the final time step showing the difficulty associated with drawing a boundary when the plume begins to dilute and fragment.

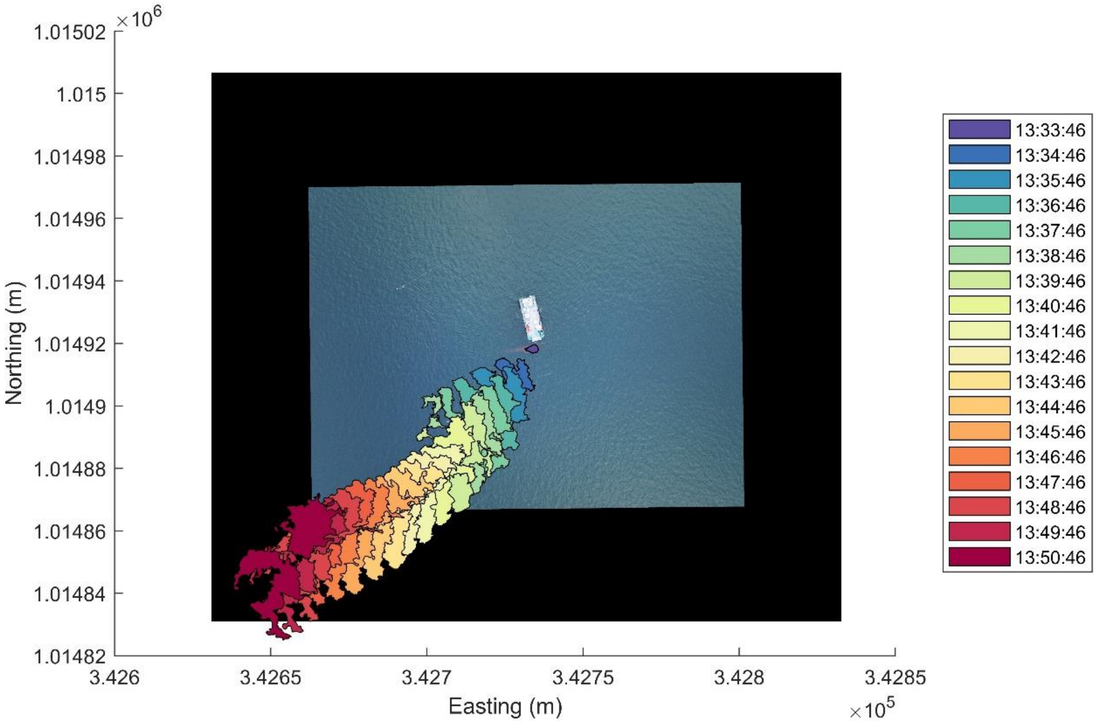

Figure 6. Extent of mapped dye plume boundary from a selection of timesteps from R3.

From the dye boundary data, the MSD is calculated (Figure 7), where each release shows an increase in MSD with lag time, indicating a continually growing plume area. The linear fit equation and the line gradient used to calculate the dispersion coefficient are provided in each subplot for the respective releases.

After approximately 10-15 minutes the dispersion of the dye plume lowers the visible concentration of the plume, making the detection of the outer boundary difficult. At this point, the size of the plume begins to shrink and fragment. This causes a reduction in the MSD that is not representative of the plume dispersion. Any data showing a continual reduction in plume area has been removed from the MSD analysis. This prevents any bias in the calculation of the final dispersion coefficient.

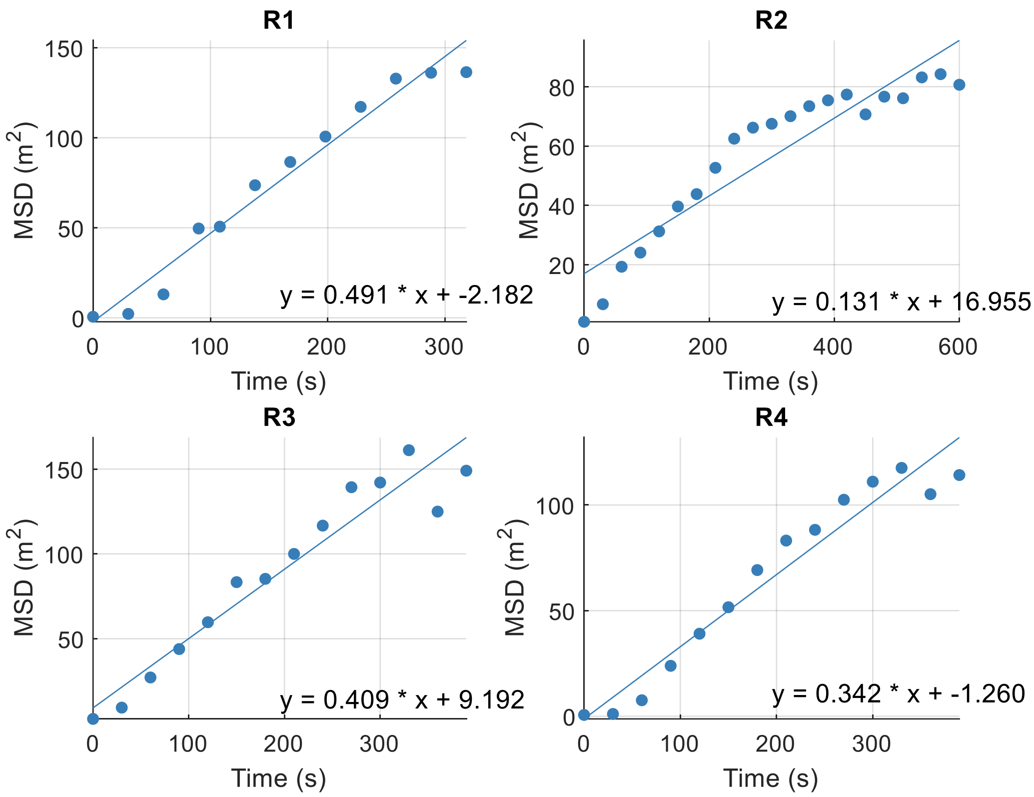

Figure 7. MSD over time with a linear fit line equation for dye releases 1 to 4.

The statistical parameters of the linear fit are provided in table 5. This shows high correlation and low errors associated with the processed data. R2 shows the highest NRMS values and lowest correlation coefficient, when compared to Figure 7, this indicates a larger variation in the rate of the plume spreading during the later part of the release. R1 and R5 shows the lowest relative error value, indicated by the clustering of data points along the fit line in Figure 7.

The results of the aerial dye plume tracking provide a range of values in the calculated dispersion coefficient. These values are all within the expected values and range from 0.053 to 0.113 m^2/s. An average horizontal dispersion coefficient of **0.09 m^2/s** is calculated from the measurements undertaken in this study.

Table 5. Line fitting statistics and dispersion coefficients for each release.

	R1	R2	R3	R4
Pearson correlation coefficient	0.984	0.933	0.963	0.972
RMS Error	8.9	9.2	13.8	10.0
NRMSE	0.066	0.110	0.087	0.085
Fit gradient	0.491	0.131	0.409	0.342
Dispersion coefficient	**0.109**	**0.053**	**0.114**	**0.076**

Drogue Release

The time-synchronised drift tracks from all releases are shown in figure 8. Drogues are shown to predominantly travel in Southeast and West directions. As time from the release point increases the drogues are shown to separate. The net transport of the drogues ranges between 195m and 917m with average speeds ranging from 0.12 and 0.29m/s. This is consistent with the data collected by the ADCP. Due to shallow water and the presence of the existing farm, longer duration drogue releases were not possible.

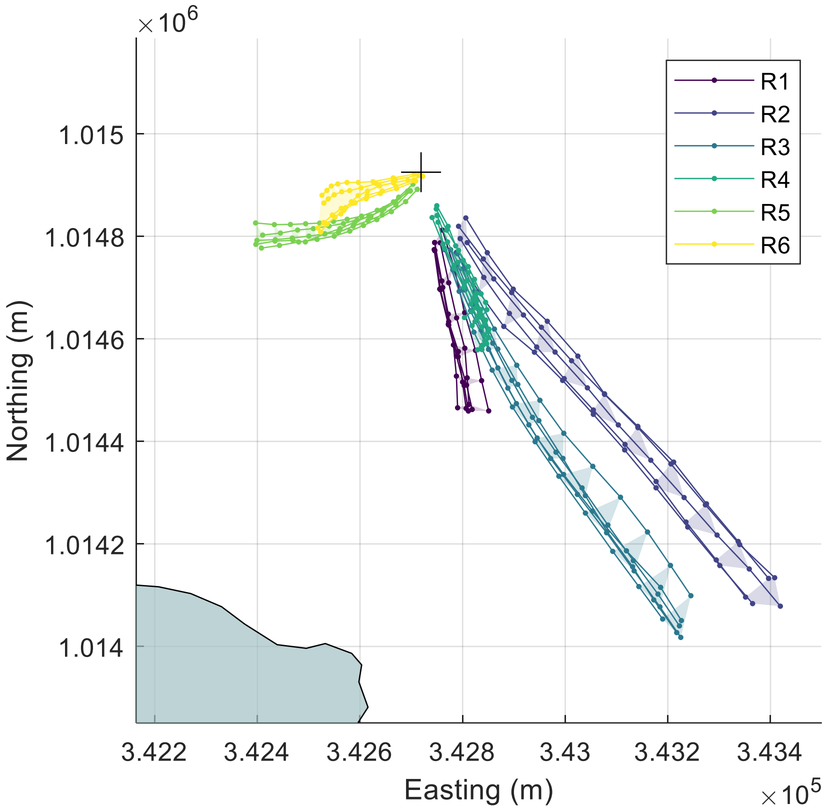

Figure 8. Time-synchronised drogue tracks for each release.

The calculated MSD of the drogue releases are shown in figure 9. A linear regression fit is applied to the data for each release. This shows while there is a continual increase in dispersion there remains a temporal variation with some instances of a reduction in the area coverage. The variation statistics, gradient and calculated dispersion coefficients are shown in table 6. Larger variations in spatial coverage of the drogues are shown in R1 and R2 and consistent dispersion is shown in R6.

The drogue calculated dispersion coefficient ranges from 0.034 to 0.233 m^2/s with an average dispersion coefficient of **0.117 m^2/s**. The largest value occurs during high water where R2 records a value of 0.233 m^2/s. The lowest dispersion occurs during R5 (0.034 m^2/s) near slack water on the ebb tide.

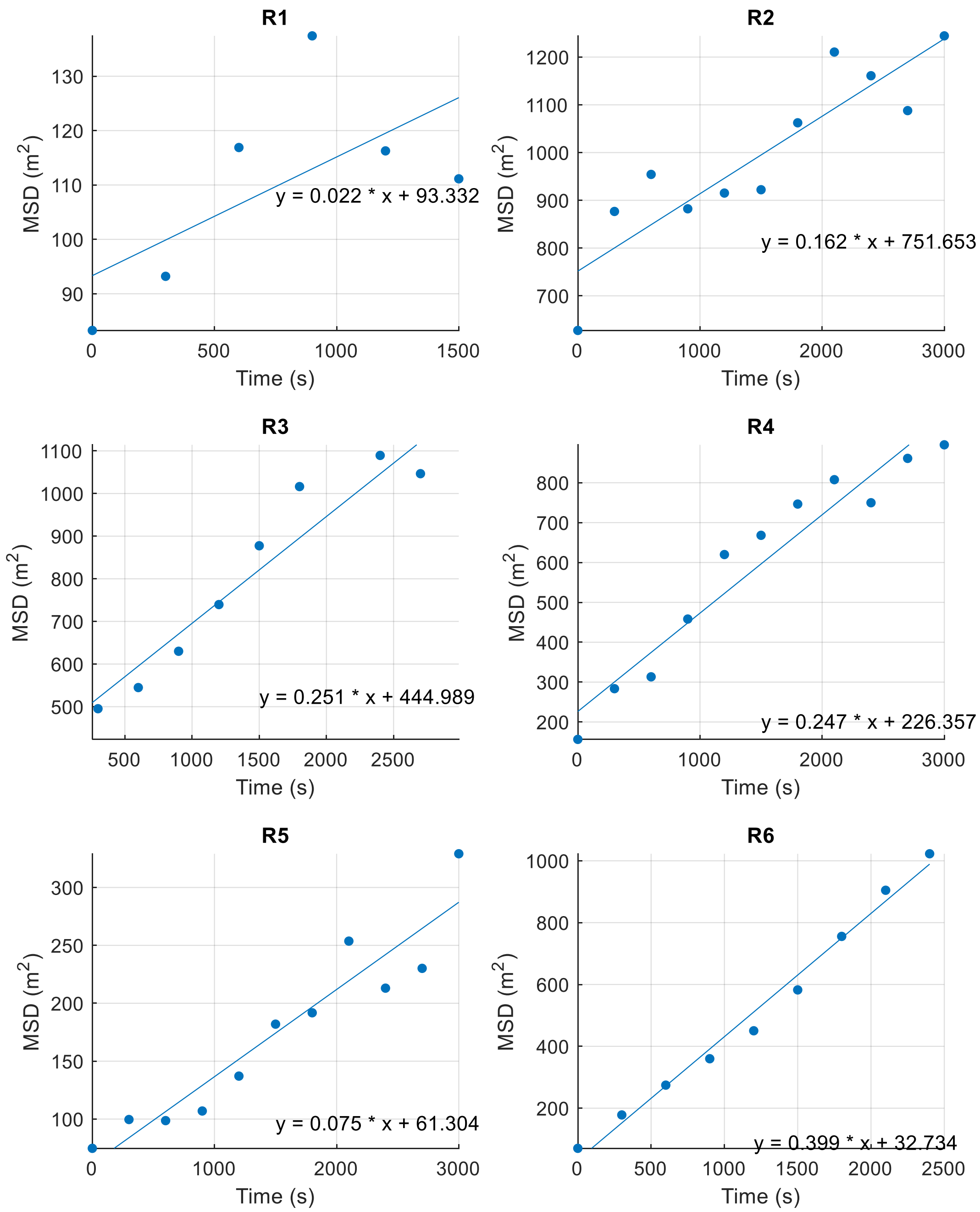

Figure 9. MSD over time with a linear fit line equation for drogue releases 1 to 6.

Table 6. Line fitting statistics and dispersion coefficients for each release.

	R1	R2	R3	R4	R5	R6
Pearson correlation coefficient	0.639	0.896	0.928	0.965	0.949	0.993
RMS Error	13.5	76.2	95.3	63.4	23.8	35.7
NRMSE	0.248	0.124	0.125	0.086	0.094	0.037
Fit gradient	0.022	0.162	0.251	0.247	0.075	0.399
Dispersion coefficient	**0.041**	**0.233**	**0.169**	**0.117**	**0.034**	**0.109**

4. Discussion

As the dye and drogue studies were completed over the same duration, there is a temptation to draw a direct comparison between the results. In ideal circumstances the results should provide very similar values. However, factors such as the highly variable nature of dispersion and the subtle time difference in the dye and drogue release mean the data cannot be used to precisely validate each other. Other contributing factors include the difference in measurement duration and the number of data points and sampling resolution of each survey type. Therefore, there is only an expectation for the result to be of a similar magnitude. The data collected reflects this, where the majority of overlapping surveys provide dispersion coefficient within a close range.

To determine a representative dispersion coefficient, the results from both survey types are averaged. This provides a mean horizontal dispersion coefficient of **0.105 m^2/s**.

5. Conclusion

This report shows a new approach for calculating horizontal dispersion coefficients using Rhodamine WT dye. The use of aerial images allows dye plumes to be mapped in 2 dimensions using a non-invasive method. The use of Rhodamine and the red colour spectrum provides a clear plume that is easily distinguished using basic computational methods. The MSD of each dye plume and the respective lag time from release allow the calculation of a dispersion coefficient.

Additional results were collected using more conventional Lagrangian drogues. Six drogues were deployed and tracked for a longer duration determination of dispersion and particle fate.

The dye study measured horizontal dispersion coefficient ranging from 0.053 to 0.113m^2/s, with an average of 0.09 m^2/s. The drogue data showed a slightly more diverse dispersion range between 0.034 to 0.233 m^2/s, with a mean value of 0.117m^2/s. When compared with the default values used within NewDepomod and BathAuto of 0.1 m^2/s, these results are shown to be within a similar range.

The use of the arial imagery to track dye plumes provides a vast improvement on the resolution of the shorter-term dispersion. This is due to the large number of data points available and the non-invasive survey method. Limitations of UAV dye surveys are optical detection and drone battery life. While these can be overcome by increasing dye release quantities and upgrading drone to more bespoke industrial models, only marginal gains in survey duration will be made. For longer duration studies (0.5 hr +), either multiple dye surveys are required, or traditional drogues survey techniques should be applied.

It is recommended that the mean dispersion coefficient of both surveys is used for future bath treatment modelling. For Quanterness, a horizontal dispersion coefficient of **0.105 m^2/s** should be used in future bath modelling applications.

References

Lumpkin, R., and Pazos M. , (2007) *"Measuring surface currents with Surface Velocity Program drifters: The instrument, its data, and some recent results"* Lagrangian Analysis and Prediction of Coastal and Ocean Dynamics, A. Griffa et al., Eds., Cambridge University Press, 39–67.

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